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A New Method for on-Line Measurement of Viscosity

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Abstract

Based on the increase type rotary encoder and the cantilever elastic element, a new kind of single cylinder rotary online viscosity sensor is designed, This article mainly introduces the principle of this sensor operation and the design calculation of the elastic element. And then further this paper shows how the finite-element method of the ANSYS is used to analyze the maximum deflection and the stress of the elastic element. Finally, the measurement error of is analyzed.

***Keywords*:** Viscosity; Sensor; Elastic element; Rotary encode

1. Introduction

For boiling sugar handicraft, syrup gradually crystallizes and become sugar in degree of super-saturation and meta-stable zone, while professionals have already recognized the importance of accurate degree of super-saturation measurement parameter in this process. Different kinds of trials have been conducted, mainly through degree of super-saturation slide rule and measured through calculating conductivity, refractive index these years. However, these methods are difficult to realize the need for online-test. It is important for online-test to indirectly measure degree of super-saturation method. There are some methods as below: conductance detection method, boiling point method, refractive method, γ ray method, viscosity method[1], etc. According to the introduction of literature, every method has its own characteristics. This article uses viscosity method, that is, regard viscosity as detection parameters.

Viscosity is one of the most important physical properties of fluid and it is an important standard characterization of the food industry, the paint industry, oil industry and other industries. Thus it is of

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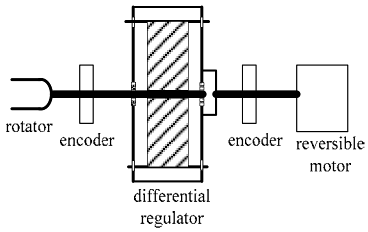
great significance to measure fluid viscosity in industrial production and basic science research. At present, the methods of measuring fluid are mainly capillary tube method, rotation, vibration method, falling ball method[2] and so on. Among these methods, the rotation method is a common method and widely applied to measure the viscosity of Newtonian fluid, non-Newtonian fluid and rheological behavior[3].

Based on above analysis, in order to achieve automatic control of boiling sugar through using the viscosity as a controlling parameter, it is necessary to design a sensor which can achieve online viscosity test. This article designs a single cylinder rotary viscosity online detection sensor which is an indirect measurement method and use cylinder as a sensitive element, which applies shearing strength principle. This sensor uses two incremental rotary encoders to test the changes of the torsion regarding the changes of the viscosity.

2. Structure of sensor and measurement principle

Single cylinder rotary viscosity online detection sensor is shown in the Fig. 1(a). The system includes U shape rotor, driving axle, photoelectric incremental rotary encoder, differential regulator, reversible motor, etc. The rotor of the sensitive element is placed in a liquid tank. Rotational energy is transferred to the axle of differential regulator. While the motor and the test torque portion are placed outside the tank. The structural principle of torsion test part is cylinder shape differential regulator shown in Fig.1 (b). When the sensor works, the driving axle is pulled by motor, and the cylinder of is differential regulator driving synchronous. There are two spring laminations distributed homogeneous according to circular distribution inside differential regulator. One end of spring laminations id connected on the driven shaft, and another end linked with limited torque rod. There are four rectangular orifice channels distributed two sides of the outer shell of the cylinder. The driving shaft depends on stirring two fixed spring laminations and the sleeve of the driven shaft, and then the driven shaft move. When the spring laminations bend in a certain angle, two limited torque rods inside the quadrate holes stir shaft sleeve in order to prevent the over bend of the spring laminations if they are overload.



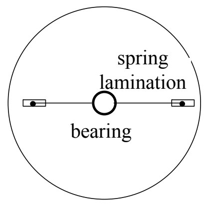


Fig.1. Cylinder rotary viscosity sensor: (a) structure, (b) testing part

Confection viscosity drives the driven shaft to generate torque in cook sugar bowl and then the torque overcome the spring laminations bending moment so that the driving shaft and the driven shaft rotate at the same time in the relative angular displacement[4,5]. The spring laminations size have a reasonable design, so the driven shaft load torque and the spring force are determined by function, spring laminations stress bending angle encoder micro angular displacement into the pulse number through the driving shaft and the driven shaft of the incremental revolving, 8051 MCU collection of the number of pulses can be converted to the corresponding relative angle, then this angle can be calculated confection viscosity and displayed.

Incremental rotary encoder is a measuring device of angle and angular velocity. The turning angle of rotary encoder is transferred into time sequence and phase displacement based on two opt coupler inside. Output of incremental rotary encoder are A, B two square-wave and Z phase pulse. Phase difference of square wave phase A and B is 90 ° electrical angle, which can easily determine the direction of rotation. The Z phase pulse revolution is used as a zero reference point for positioning. The sensors with two E40H hollow incremental rotary encoders. With which, the output of encoder 1 is Z phase pulse only, and outputs of encoder 2 are B phase pulse (pulses are 5000P/ R, resolution is 0.072°)and Z phase pulse. Assumed stationary, the encoder 1 and 2 of the zero holes is substantially aligned. The drive shaft is rotated to drive the encoder 1 synchronous rotation, the driven shaft rotates to drive the encoder 2 synchronous rotation. When the encoder 1 of Z phase output a pulse (start signal), MCU begin to record the B phase pulse number of the encoder 2 (a difference of perspective),the encoder 2 of Z phase output a pulse (termination signal) to stop recording B phase pulse count. This MCU records the number of B phase pulse corresponding to the two axis of rotation on the deviation angle[6].

It is difficult to align zero position hole to install encoder 1 and encoder 2, but it can be eliminated by using software. It means that, if it is non-loaded, the deviation angle of deviation obtained from the method above is the initial angle of A and B of two deviation, so the deviation angle can be add into this angle of deviation value when actual measurements conduct. Because different kinds of friction lead to friction torque similarly, it can measure the initial angle of deviation of the spring laminations under this idle. When working, the measured angle minus this initial angle of bend is equal to the actual angle of bend.

3. The load range of the sensor

In order to gain the range of the massecuite viscosity, we take sample tests on the key operation points during the process of boiling sugar in a sugar factory. We use SNB-1 digital viscosity measurement to conduct experiments, due to massecuite which belongs to non-Newtonian fluid and besides temperature, its viscosity mainly depends on the size of shearing rate. Experimental temperature is the same as boiling sugar temperature on operation point ,which pick up sampling and all the measurement of rotate speed are 30r/min. Measuring viscosity in each operation point shows in the Fig.2. From that figure, the range of variation of viscosity is between 0.6 and 4.5 Pa.s. So the actual value is 0.5～10Pa.s.

Based on SNB-1figure viscometer measuring rotor dimension proportion, this contrivable cylindrical rotor measurement is: radius $r_1 = 0.04\text{m}$, tall $h = 0.12\text{m}$. Based on cylinder stickiness torsion formula $M = 4\pi\eta h\omega r_1^2$, we can calculate the range of the rotor's stickiness torsion 3.7891 $N \cdot mm$~75.7963 $N \cdot mm$.

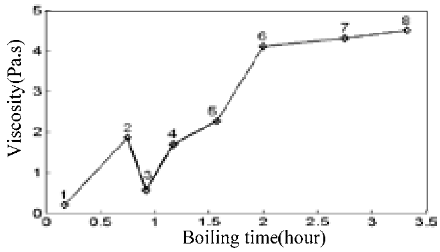


Fig. 2. The process of boiling sugar curve of viscosity versus time

4. Structural design of the elastic element of cantilever beam

4.1 The choices of material and length

The spring lamination here is beryllium bronze, model number is QBe2. Which is considered as the material of the elastic sensitive element in early stage. Comparing with stainless steel, its elastic stored energy is relative high. It is beneficial to improve the sensitivity of elastic element and to reduce elastic hysteresis and aftereffect. It has other merits, such as no magnetism, fatigue resistance, welding performance[7].

Beryllium bronze is provided by Jiangyin Chuang-Yi metal material Co, LTD. The physical property of provides are: admissible stress is 588~640 MPa, modulus of elasticity is $E = 130 \times 10^3 N/mm^2$, density is $\rho = 8.26 \times 10^{-6} Kg/mm^3$. In order to ensure the spring lamination has the appropriate angle of bend and the weighted balance within the load range, the length of spring lamination is 40mm.

4.2 The design calculation of thickness

When the beam's flexural vibrations occur, as a general rule, it has an influence on the beam, and it leads to transformation, shear deformation and rotary inertia and so on. For cross sectional dimensions and length in terms of relative small slender beam, the former has a relative big influence and the effects of the later situations can be ignored. From vibration knowledge[8], the lowest natural frequency of the cantilever beam of the homogeneity cross-section is:

$$\omega_n = \frac{3.53}{L^2}\sqrt{\frac{EI}{\rho A}} = \frac{3.53}{L^2}\sqrt{\frac{Eh^2}{12\rho}} \tag{1}$$

Because the viscosity of the non-Newtonian fluid is related to the rate of shear, so this sensor measures constant rotate speed 30r/min. It means that the maximum of circular frequency for measuring spindle is $\omega = 3.1415 rad/s$. In order to reduce the measurement of dynamic errors to small range, it requires that natural frequency of vibration of the elastic element should be at least the highest frequency of measuring process 3-10 times. Therefore, setting $\omega_n = 44 rad/s$, meaning 14 times of ω. From Eq.(1), the measurements that are relevant to natural frequency are L and H. From the structure of this design, L depends on the external diameter of the principle axis and the inner diameter of driven shaft outer sleeve, L of this sensor is equal to 40mm, the select material of the spring lamination is QBe2, known $E = 130 \times 10^3 N/mm^2$、$\rho = 8.26 \times 10^{-6} Kg/mm^3$, substitute Eq.(1) and then get:

$$h = \sqrt{\frac{(L^2\omega_n)^2}{3.53^2} \cdot \frac{12\rho}{E}} \tag{2}$$

After we calculate and get h=0.5507mm. Consider the standard of QBe2, in the market, h is equal to 0.5mm. And then substitute the actual thickness into Eq.(2), we get the actual lowest natural frequency of the spring lamination is $\omega_n = 39.9497 rad/s$, it is 13 times of ω. It makes the measurement of the dynamitic errors to small range.

4.3 The design calculation of the width

The confirmation of the width generally guarantees the conditions that have sufficient angle outputs and the adequate strength and the rigidity of the spring laminations. The relationship between the working displacement of the spring laminations y and output strain value of ε is necessary to be nonlinear based on many literatures. However, the size of the nonlinearity is different. It can ensure that the working transformation of the spring laminations is the optimal linear transformation. This can be deduced by mechanics of materials:

$$\frac{\varepsilon}{y} = \frac{3h}{2L^2}[1 - \frac{3y^2}{5L^2}] \tag{3}$$

The nonlinear value is relevant to $\frac{y}{L}$, controlling $\frac{y}{L}$ value is one of the essential conditions that ensure linearity. In order to ensure sufficient angle output, the value of $\frac{y}{L}$ is equal to 1/15, meaning nonlinearity. The nonlinearity value is $\frac{3y^2}{5L^2} = 0.2667\%$. The working transformation formula of the cantilever beam can be deduced[9]:

$$\frac{y_{\mathrm{MAX}}}{\mathrm{L}} = \frac{1}{15} = \frac{4p\mathrm{L}^2}{Ebh^3} \tag{4}$$

With Eq. (4), we can deduce that:

$$b = \frac{60p\mathrm{L}^2}{Eh^3} \tag{5}$$

The range of variation of trochanteric stickiness moment M is: 3.7891 $N \cdot mm$~75.7963 $N \cdot mm$. Because two viscous torque M rotors are used, each of the torque M rotors ranges:1.8946 $N \cdot mm$ ~37.8982 $N \cdot mm$.

In order to guarantee the nonlinearity value of the spring lamination under maximum transformation reaching to 0.2667%, so we use the biggest torque to calculate $M = 37.8982\mathrm{N.mm}$. Shaft radius is $\mathrm{r} = 4\mathrm{mm}$. Consider the thickness of welded joints $\mathrm{t} = 1\mathrm{mm}$. Also $\mathrm{L} = 40\mathrm{mm}$, the radius of the rotor for $\mathrm{R} = 40\mathrm{mm}$, so we have:

$$p_{\mathrm{MAX}} = \frac{M}{\mathrm{L} + \mathrm{t} + r} = 0.8422\mathrm{N} \tag{6}$$

By $\mathrm{L} = 40\mathrm{mm}$, $\mathrm{E} = 130 \times 10^3\,\mathrm{N/mm^2}$, $\mathrm{h} = 0.5\,\mathrm{mm}$, generation into Eq.(4), we have: $\mathrm{b} = 4.9755\,\mathrm{mm}$, considering the market beryllium copper plate of the specifications of the thin green, take $\mathrm{b} = 5$ mm, the actual maximum deformation of nonlinear term for 0.2641%.

5. Finite element analysis of cantilever beam elastic element

Based on previous design calculation, the size of the elastic element is got. Using this size and the ANSYS finite-element analysis software, we can analyze the internal stress distribution of cantilever beam elastic element and the deflection situation of the forced direction[10]. Shown as Fig. 3:

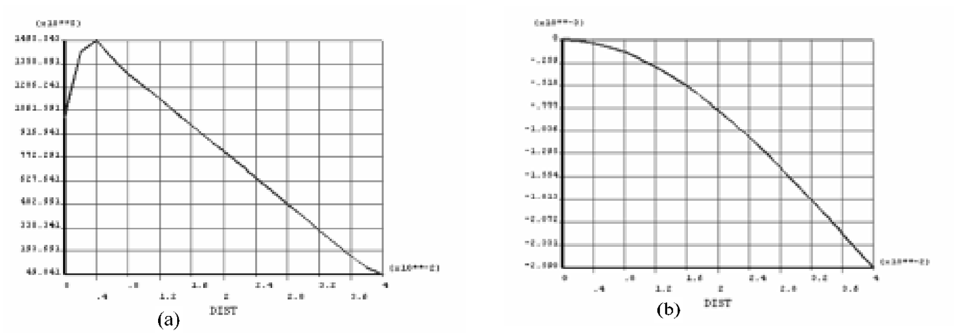


Fig. 3. Finite-element analysis: (a) stress distribution, (b) cantilever deflection

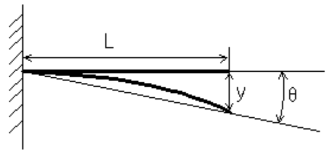


Fig. 4. Cantilever beam bending deformation after the deflection of curve.

The biggest allowable stress of beam is $\sigma_{\mathrm{MAX}} = 158\mathrm{MPa}$ .The maximum deflection of the beam is $\mathrm{y}_{\mathrm{MAX}} = 2.596\mathrm{mm}$. The deflection angle for the beam is $\theta = \arctan(\frac{y}{L})$, shown as Fig.4. So the maximum deflection angle beam is $\theta_{\mathrm{MAX}} = \arctan(\frac{\mathrm{y}_{\mathrm{MAX}}}{\mathrm{L}}) = 3.713^{\circ}$.

6. Deviation analysis

The precision of the sensor indicates the degree of closeness between numerical readings and observed actual values. It mainly refers to the nonlinear errors of the sensor. Based on previous analysis, we have already known that the nonlinear value of the spring lamination in the actual maximum transformation is 0.2641%. From the structure of the sensors, in order to prevent the radial tensile stress happening, the spring lamination of driven shaft outer sleeve is not fixed. So when the spring lamination has relative big deflection, its carrying capability point removes outside. Equivalently, the length of the spring lamination increases. The maximum deflection under beam is $\mathrm{y}_{\mathrm{MAX}} = 2.596\mathrm{mm}$, then calculate the quantity of outside motion of the carrying capability point of the spring lamination is $\Delta\mathrm{L} = 0.084\mathrm{mm}$. Therefore, we can calculate the actual beam deflection under the maximum deflection y=2.608mm. The measurement of the angle error is $\Delta\theta = \arctan(\frac{y}{L}) - \arctan(\frac{y_{MAX}}{L}) = 0.017^{\circ}$.

7. Conclusion

The structure of the single cylinder rotary viscosity online detection sensor is novel. Through the detailed design calculation, the principle of this sensor operation is feasible. When the test system of this sensor works, it can directly input signals into MCU and the collection and the process of data are under the MCU control, this system can reveal viscosity data online. At the same time, this new kind structure of this sensor can be suitable for other torque ranges through reasonable design of spring lamination.

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